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Scenario analysis of hypothetical site conditions for geological CO_2 sequestration in Japan

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Abstract

For the practical application of deep geological CO_2 sequestration in Japan, it is necessary to assure the safety of the sequestration method and technology to achieve public acceptance. For this purpose, it is also necessary to carry out risk assessments and scenario analysis taking into account typical Japanese geological conditions. A scenario analysis procedure was evaluated by using hypothetical geological information reflecting the actual geology in Japan. A new FEP database (RITE-DB) was created for application to Japanese geology because Japan has complicated geological structures which include folds, faults and fractures. FEPs are features, events and processes that are relevant to the long-term safety and performance of the sequestration system after injection of CO_2. The scenario analysis with the RITE-DB identified important scenarios, i.e. a fault scenario, a seal failure scenario, etc. and many phenomena sequences in these scenarios. The process of identifying the scenarios and phenomena was judged to be exhaustive. The results will inform quantitative safety analysis and site design.

Keywords: FEP; risk; scenario; geological CO_2 sequestration

1. Introduction

The geological storage of CO_2 could make a significant contribution to the mitigation of anthropogenic emissions of CO_2 (Holloway, 1996). The feasibility of the geological storage of CO_2 as a mitigation measure depends on a number of factors. Most of the potential safety impacts of the geological storage of CO_2 are related to the migration of CO_2 from the storage reservoir or aquifer back to the accessible near surface environment. Systems analysis has been successfully applied to assessments of the performance and safety of the geological disposal of radioactive wastes and this approach is now being applied to the long-term geological storage of CO_2. The use of

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FEPs to describe the storage concept to be evaluated is a powerful tool to ensure that the assessments incorporate comprehensive consideration of all potentially significant factors. FEPs are the feature, events and processes that are relevant to the behavior of CO_2 in the system being assessed.

A new FEP database (RITE-DB) for the geological storage of CO_2 in Japan has been developed with the chosen FEPs being included for their relevance to the long-term safety and performance of the storage system after injection of CO_2 has been completed and the injection boreholes have been sealed. Some FEPs associated with the injection phase are nevertheless considered where these can affect long-term performance.

2. FEP database (RITE-DB)

2.1. Aim of introducing a FEP database to Japan

To establish a FEP database for application in Japan, it is necessary to include major phenomena that occur in Japan that are of concern for CO_2 sequestration. Typical phenomena in Japan are different from those in most other countries that are considering CO_2 storage. Japan is an island arc that occurs at plate boundaries and is affected by the monsoon. These characteristic phenomena in Japan are important phenomena in terms of CO_2 sequestration and have to be included in the FEP database. We promote the construction of a FEP database from the standpoint of comprehensiveness of Japanese phenomena of concern to CO_2 sequestration.

After construction of the FEP database including Japanese phenomena, we constructed scenarios for some hypothetical sites. These sites reflect Japanese geology by using information from actual sites in Japan. At this step, we confirmed the applicability of the FEP database to Japanese sites.

Through the construction of the FEP database and trial construction of scenarios, we investigated the processes by which the FEP database can be applied in Japan and issues connected with using the FEP database.

2.2. Contents of FEP database (RITE-DB)

A FEP database named the ‘RITE-DB’ was modified and extended after a generic FEP database (created by Quintessa Ltd (Savage et al., 2004). Each FEP record in the ‘RITE-DB’ includes a description, explanation of the FEP’s relevance to the safety of long-term geological CO_2 storage, bibliographical references and links to relevant web pages. The RITE-DB was improved by adding new FEPs concerning Japan to Quintessa's FEP database and some tools to manipulate FEPs. There are FEPs that may be applicable in Japan and outside Japan, for example, the properties of CO_2. However, it was necessary to add some new FEPs and modify FEP descriptions to provide more detail about characteristics of Japan. There are eight main FEP categories in the RITE-DB. Category 0 is the Assessment Basis category. Category 1 is the External Factors category. Category 2 is the CO_2 Storage category. Category 3 is

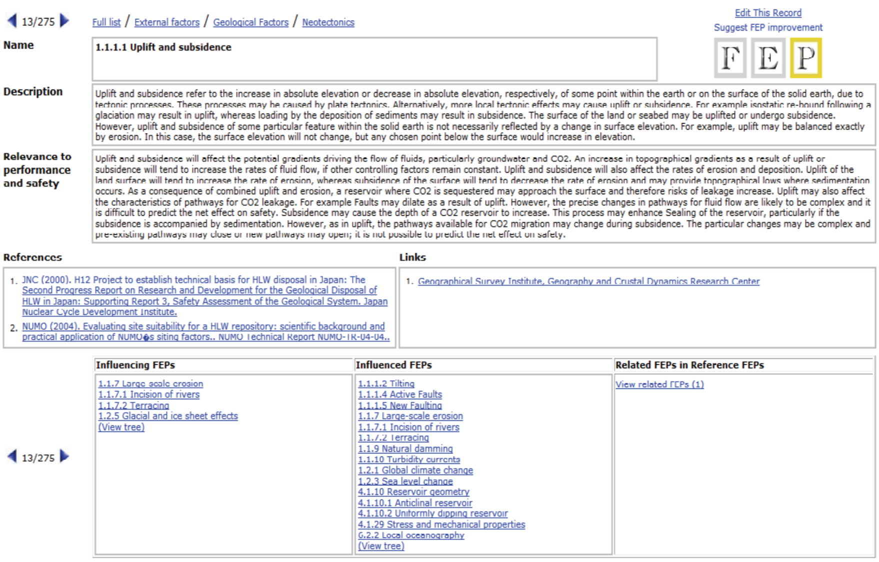

Figure1: Example of a FEP record in the RITE-DB

the CO_2 Properties, Interactions and Transport category. Category 4 is the Geosphere category. Category 5 is the Boreholes category. Category 6 is the Near-Surface Environment category. Category 7 is the Impacts category. There are subcategories of FEPs under each of the main categories. The total number of FEPs in the RITE-DB is 275. The RITE-DB isn't based on site specific information and therefore it remains a generic FEP database.

Japan exists near a plate subduction boundary and there are marked seasonal changes in Japan related to the monsoon. In these two ways Japan is different from continental land masses such as those of Canada or Europe. Typical geological and climatic phenomena relevant to Japan were added and records of existing FEPs were modified. For example, subduction is one of the typical Japanese geological processes. Neotectonics is, therefore, subcategorized into more specific processes such as "1.1.1.1 Uplift and subsidence", "1.1.1.2 Tilting", "1.1.1.3 Active folding", "1.1.1.4 Active Faults", "1.1.1.5 New Faulting" and "1.1.1.6 Accretion". The numbers prior to these FEPs are for discrimination in the RITE-DB. Volcanic activity and seismicity are also subcategorized. Typhoons are one of the typical climatic phenomena added.

Figure2: Example of a Tree view in RITE-DB

Figure 1 shows an example of a FEP record in the RITE-DB,"1.1.1.1 Uplift and subsidence" . It includes a description of the FEP and an additional explanation of the FEP's "Relevance to performance and safety". Relationships between one FEP and another FEP are also recorded in the RITE-DB, which are shown in the entry as "Influencing FEPs" and "Influenced FEPs". All of the relationships between FEPs were determined by expert judgments. Tools were added to allow trees and PIDs (Process Influencing Diagram) to be viewed.

These two functions can show relationships between FEPs visually. A tree view can show FEPs that are influenced by a FEP of interest, which appears at the top of a tree-shaped structure. Similarly, FEPs that influence the FEP of interest can be shown in a tree. Figure 2 shows an example of the tree view.

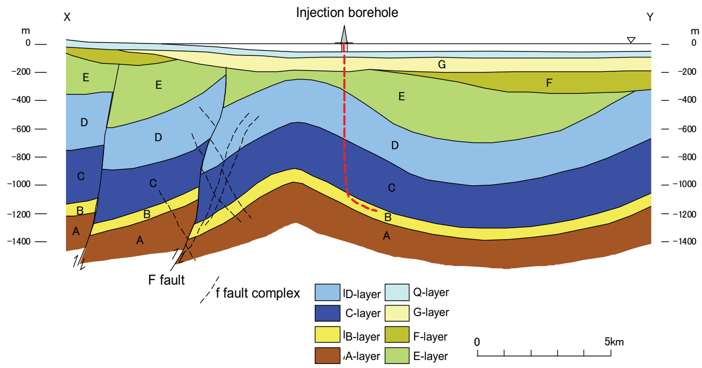

Figure3: Geological features of a hypothetical site with a structural trap

3. Scenario Analysis with hypothetical site conditions

3.1. Hypothetical Sites

Two types of hypothetical site conditions were defined and used for the scenario analysis. The geology of one site has a dome shaped anticlinal cap rock structure and the other has no such cap rock structure, as shown in Figure 3 and Figure 4 respectively. In

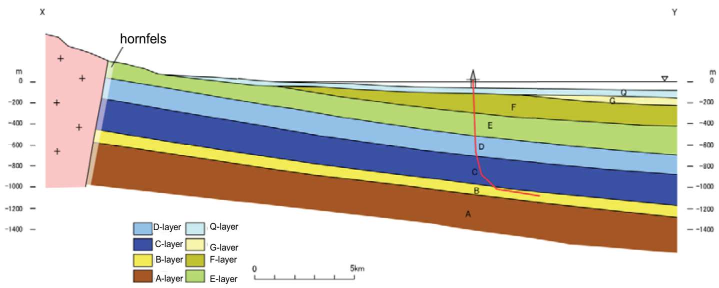

Figure4: Features of a hypothetical site with a non-structural trap

this paper, the site with a dome shaped cap rock is described as a 'structural site' and the other site without a dome-shaped cap rock is described as a 'nonstructural site'. Conditions at both of the structural and the nonstructural sites were based on actual sites in Japan. They were both assumed to be located in a typical subduction zone setting, and their geologies mainly consist of sedimentary rocks formed from the Miocene period to the Pleistocene period.

Each hypothetical site is defined to have a reservoir with a capacity sufficient for a total of 30,000,000 tons of CO_2, so that each site has an annual injection capacity of 1,000,000 tons per year over a period of 30 years.

To assess the safety of geological CO_2 sequestration at the hypothetical sites, information about their geological structures is necessary because these structures determine the nature of the CO_2 trap in each case. Information about the characteristics of faults and fractures is particularly necessary because advection of groundwater and CO_2 is decided mainly by these characteristics. Also, the permeability and porosity of the rocks are important because advection of groundwater and CO_2 is described by these parameters. Pore water dissolving CO_2 may chemically interact with rock minerals. At the point of interaction between minerals and pore water, chemical composition of groundwater and mineral species are necessary for assessment of the safety on CO_2 sequestration. Also, information about the direction of groundwater flow is necessary to evaluate the advection of groundwater containing CO_2 and free CO_2. The geological history is necessary to evaluate the possibility that the geological environment may change in the future after the injection of CO_2 has ceased and the site has been closed. Information about the hypothetical sites consists of the following items. First is information about their geological structures, which includes field survey observations and information about geography, geology, rock facies, faults, intrusions, distributions of cap rocks and aquifers, possible CO_2 storage capacity, fractures, current stress states, ground temperature and hydrological characteristics of the rock, including porosity. Second is mineral information, which includes mineral species. Third is information about groundwater, which includes the chemical composition and residence time of the groundwater. Fourth is the geological history, which includes knowledge relevant for predicting the future environment.

Table1: Prerequisite conditions for scenarios of hypothetical sites

FEP number	FEP name	prerequisite conditions for constructing the scenario at hypothetical site
S.0	Assessment basis	
S.0.1	Purpose of the assessment	The construction of scenarios about geological CO_2 sequestration is executed on hypothetical sites in Japan.
S.0.2	Endpoints of interest	Bottom of the sea is assumed as a leakage point of CO_2 from CO_2 sequestration point.
S.0.3	Spatial domain of interest	About structural hypothetical site, spatial domain is almost 20 km square around the injection well and from GL-1200m to bottom of the sea. Nonstructural hypothetical site was made a range with all sides of almost 30 the km in surroundings from the injection well within the range from GL-1200m to bottom of the sea.
S.0.4	Timescales of interest	50 years are assumed as a short-term time scale and 10,000-100,000 years are assumed as a long-term time scale.
S.0.5	Sequestration assumptions	The quantity of CO_2 sequestered is 30 million tons.
S.0.6	Future human action assumptions	The future human action other than the human intrusion scenario is not considered.
S.0.7	Legal and regulatory framework	The legal and regulatory framework is not considered.
S.0.8	Model and data issues	The numerical model or the input data used for the simulation executed to the scenario are not considered.

Table2: An internally consistent set of FEPs for the structural site

number	name	number	name
G.1.1.3.2	Seismic vibration	G.3.3.5	Dissolution in formation fluids
G.2.1.1.2	Structural trapping	G.3.3.8	Co-migration of other gases
G.2.1.1.3	Aquifer storage	G.4.1.3.1	Dome structure
G.2.1.2	CO_2 quantities, injection rate	G.4.1.8.1	Coal
G.2.1.3	CO_2 composition	G.4.1.10.1	Anticlinal reservoir
G.2.1.5	Schedule and planning	G.4.1.12	Cap rock or sealing formation
G.2.1.6	Pre-closure administrative control	G.4.1.13	Permeability reduction of cap-rock
G.2.1.7	Pre-closure monitoring of storage	G.4.1.14.1	Additional lateral sealing
G.2.1.8	Quality control	G.4.1.14.2	Vertical stratigraphical sealing
G.2.1.10	Overpressuring	G.4.1.15	Lithology
G.2.2.1	Post-closure administrative control	G.4.1.19	Secondary mineral formation
G.2.2.2	Post-closure monitoring of storage	G.4.1.20	Mineral precipitation
G.2.2.3	Records and markers	G.4.1.21	Mineral dissolution
G.3.1.1	Physical properties of CO_2	G.4.1.27	Formation pressure
G.3.1.2	CO_2 phase behaviour	G.4.1.27.1	Pore pressure
G.3.1.3	CO_2 solubility and aqueous speciation	G.4.1.27.2	Lithostatic pressure
G.3.2.1	Effects of pressurisation of reservoir on caprock	G.4.1.28	Temperature gradient
G.3.2.2	Effects of pressurisation on reservoir fluids	G.4.1.29	Stress and mechanical properties
G.3.2.3	Interaction with hydrocarbons	G.4.1.30	Petrophysical properties
G.3.2.5	Mechanical processes and conditions	G.4.2.1	Fluid properties
G.3.2.9	Water chemistry	G.4.2.1.3	Fluid density
G.3.2.11	Sorption and desorption of CO_2	G.4.2.1.4	Fluid viscosity
G.3.2.12	Heavy metal release	G.4.2.2.1	Head gradient
G.3.2.13.1	Mineral dissolution and precipitation	G.4.2.3	Hydrocarbons
G.3.2.13.2	Ion exchange	G.5.1.1	Formation damage
G.3.2.13.3	Dessication of clay	G.5.1.2	Well lining and completion
G.3.2.14	Gas chemistry	G.5.1.4	Monitoring wells
G.3.2.15	Gas stripping	G.5.1.5	Well records
G.3.2.16	Gas hydrates	G.5.2.1	Closure and sealing of boreholes
G.3.2.17	Biogeochemistry	G.7.1.1	Loss of containment
G.3.3.1	Advection of free CO_2	G.7.2.3	Release to the atmosphere
G.3.3.2	Buoyancy-driven flow	G.7.2.4	Release to the seabed
G.3.3.4	Displacement of formation fluids	G.7.2.6	Modified hydrology and hydrogeology

3.2. Extraction of an internally consistent set of FEPs and FEPs that may constitute a risk at the hypothetical sites

In advance of the scenario analysis of each hypothetical site, prerequisite conditions were determined (Table 1). Regulatory restrictions were not considered because they are not yet decided in Japan. The injection point is located 10 kilometers offshore where the depth of water is 50m. The CO_2 is injected into a sub-seabed reservoir at a depth of 1000m below sea level, from a facility constructed at the sea surface. The area considered extends for several 10's of kilometers from the injection point. Two time periods were considered: a short period of several 10's of years; and a long period of several 10's of thousands of years. Human activities besides human intrusion were not considered. The probability of CO_2 release, affect on human health or marine species and so on were used as evaluation indicators. In this research, release to the sea bed is defined as an end point of the assessment. Because regulatory requirements are not decided at this time, FEP S.0.7 was not considered.

Screening of all the General FEPs was conducted in two steps. At the first screening, all the FEPs that have the possibility to cause a risk of CO_2 leakage were extracted. Also, an internally consistent set of FEPs were extracted. At the second screening, all these FEPs that have an associated risk were ranked for each hypothetical site. Scenario-defining FEPs were extracted at the second screening.

3.2.1. First screening of General FEPs

In this first screening, FEPs that may carry a risk for the hypothetical sites were extracted. This screening was conducted on the basis of each hypothetical site's data and expert judgment. The following FEPs that do not carry a risk were excluded. Firstly, FEPs that were unrelated to the construction of a scenario, for example, prerequisite conditions (Timescales of interest, Purpose of the assessment and so on) were excluded. Secondly, FEPs that do not exist at the site, judging from the site's data, were excluded. Thirdly, those FEPs that would have effects that can be taken into account by other FEPs were excluded. Finally, an internally consistent set of FEPs that are not the initiators of risks remained. For the structural site these FEPs are shown in Table 2.

3.2.2. Second screening of FEPs

In the second screening, the priorities of the phenomena to be considered were discussed from two points of view. One perspective is the possibility of each FEP occurring over the short and long time scales and the other perspective is the possible impacts of its occurrence. Each FEP extracted at the first screening as a possible cause of risk was ranked on the basis of possibility and the possible impacts of its occurrence. The possibility of each FEP to produce CO_2 release was ranked using both ranks of possibility and possible impacts of its occurrence. The possibility of a FEP's occurrence was evaluated over two time scales. One time scale extends until shortly after site closure and the other is up to 100,000 years after closure. Possibility was ranked at four levels: High, Uncertain, Low and None. 'High' is the rank assigned to a phenomenon that is almost certain to occur in the assessment period. 'Uncertain' is the rank assigned to a phenomenon that occurs if appropriate conditions are satisfied, but whether or not it will occur is uncertain in the assessment period. 'Low' is the rank assigned to a phenomenon that has only a low possibility of occurring in the assessment period. 'None' is the rank assigned to a phenomenon that almost certainly will not occur in the assessment period. Next, FEPs are ranked on the basis of their impact on CO_2 release from the sequestration reservoir to the sea bed, if the FEP occurs. A FEP was ranked 'High' if the FEP itself has the potential to act as a release pathway or represents a mechanism that may produce such a pathway directly. A FEP was ranked as 'Moderate' if it can be a process that may produce a pathway indirectly. A FEP was ranked 'Low' if it can be a process to produce a pathway indirectly, but the possibility of this occurring was judged to be low. A FEP that is not a process or feature that can produce a potential pathway directly or indirectly was ranked as 'None'. Using two types of ranking according to the possibility of a FEP's occurrence in the assessment period and the possible impacts of its occurrence on CO_2 release, FEPs

Table3: Risk rank

The possible impacts of its occurrence to CO_2 release \ Possibility of occurrence (shortly after closure or 100,000 years after closure)	High	Uncertain	Low	None
High	High	High	Low	None
Moderate	Moderate	Moderate	Low	None
Low	Low	Low	Low	None
None	None	None	None	None

were ranked on the basis of Table3. There are two ranks, one for a time shortly after closure and one for a long time after closure. The higher rank was selected as the rank of the FEP. As a result, FEPs with a high possibility to produce CO_2 release at the hypothetical sites were ranked. 'Scenario-defining' FEPs were then selected from these FEPs.

'Scenario defining' FEPs for the structural site are "G.3.3.3 Fault valving", "G.4.1.4 Fault zone", "G.4.1.5 Antithetic fault", "G.4.1.6 Fracture zones", "G.4.1.7 Fault breccia", "G.4.1.26.1 Undetected faults", "G.5.2.2 Seal failure" and "G.1.3.5 Human intrusion". To define independent scenarios, "G.4.1.4 Fault zone" and "G.4.1.26.1 Undetected faults", "G.5.2.2 Seal failure" and "G.1.3.5 Human intrusion" were selected. Other upper FEPs such as "G.3.3.3 Fault valving", "G.4.1.5 Antithetic fault", "G.4.1.6 Fracture zones" and "G.4.1.7 Fault breccia" are integrated to "G.4.1.4 Fault zone" or "G.4.1.26.1 Undetected faults". As a result, four types of important scenario were selected for the structural site with cap rock structure: a fault zone scenario, a seal failure scenario, an undetected faults scenario and a human intrusion scenario. An undetected faults scenario, a seal failure scenario and a human intrusion scenario were selected for the nonstructural site. A fault zone scenario is not relevant for the nonstructural site because there is no fault at this site.

3.3. FEP chains in each scenario

Chains of FEPs were based on those FEPs that were extracted by screening, by using the tree view tools of the RITE-DB. From all the chains of each scenario, important chains were extracted that start from the FEP with a high possibility to impact upon CO_2 release and ends at a FEP resulting in release to sea bed . Firstly, the FEP chains containing repetition were omitted. Secondly, FEPs were consolidated on the basis of their characteristics. Thirdly, chains containing "3.3.3 Fault valving" the possibility for which is unknown were omitted. Finally, chains containing a number of CO_2 migration mechanisms, chains that are included in other chains and chains containing conflicting FEPs in time were omitted. As an example, FEP chains in the fault zone scenario for the structural hypothetical sites are shown in the following paragraph.

The fault zone scenario for the structural hypothetical site has three FEP chains. The first chain is "4.1.4 Fault zone -> 4.1.30 Petrophysical properties -> 3.3.1 Advection of free CO_2 -> 7.2.7 Modified hydrology and hydrogeology -> 7.2.4 Release to the seabed". In this chain, permeability of the fault is larger than supposed, critical CO_2 moves and hydrology of groundwater changes. As a result, groundwater dissolving CO_2 moves to the sea bed. Second and third FEP chains are "4.1.4 Fault zone -> 2.1.1.2 Structural trapping -> 3.3.4 Displacement of formation fluids -> 4.2.1.3 Fluid density -> 3.3.2 Buoyancy-driven flow -> 4.2.2.1 Head gradient -> 7.2.7 Modified hydrology and hydrogeology -> 7.2.4 Release to the seabed" and "4.1.4 Fault zone -> 2.1.1.2 Structural trapping -> 3.3.4 Displacement of formation fluids -> 4.2.1.3 Fluid density -> 4.2.2.1 Head gradient -> 7.2.7 Modified hydrology and hydrogeology -> 7.1.1 Loss of containment -> 7.2.4 Release to the seabed". In these chains, the permeability of the fault is larger than supposed, advection of groundwater is induced and groundwater moves. As a result, groundwater dissolving CO_2 is encouraged to reach the sea bed.

The main FEP chains for the hypothetical structural site are summarized in Table 4.

Table4: FEPs in each scenario at the structural hypothetical site

Fault zones scenario	Undetected faults scenario	Seal failure scenario	Human intrusion scenario
G.3.3.3 Fault valving	G.3.3.3 Fault valving	G.5.2.2 Seal failure	G.1.3.5 Human intrusion
G.4.1.4 Fault zone	G.4.1.6 Fracture zones		
G.4.1.5 Antithetic fault	G.4.1.7 Fault breccia		
G.4.1.6 Fracture zones	G.4.1.26.1 Undetected faults		
G.4.1.7 Fault breccia			

(*) Four scenarios contain FEPs in Table 2 that comes up on a steady basis.

4. Conclusion

A new FEP database, the RITE-DB, was created to contain FEPs characteristic of Japan. It was considered that Japan exists on a typical plate subduction zone, and that there are distinctive seasonal changes in Japan.

The RITE-DB contains relationships between influenced FEPs and influencing FEPs and can show relationships between FEPs by two functions, the tree-diagram tool and the PID (Process Influence Diagram) tool.

Using the RITE-DB, scenarios have been defined for two hypothetical sites, one at which there is a structural CO_2 trap (termed the 'structural site') and one at which there is a hydrodynamic trap (termed the 'nonstructural site'). By expert judgment, FEPs that have the possibility to cause a risk are ranked by multiplying the possibility of their occurrence and the extent of impact on CO_2 leakage. The possibility and the extent of impact are respectively ranked at one of four levels. However, this method is not quantitative and the qualitative judgments made must be discussed among experts. As a result, four scenarios were extracted for the structural site and three scenarios were extracted for the nonstructural site. The four scenarios for the structural hypothetical site are: a human intrusion scenario; a fault zones scenario; an undetected faults scenario; and a seal failure scenario. Also, a human intrusion scenario, an undetected faults scenario and a seal failure scenario were selected for the nonstructural hypothetical site. Important chains containing the CO_2 movement processes for the assessment were extracted from all the chains of each scenario.

Extracting scenarios by Using RITE-DB has transparency, completeness and traceability. Also, the RITE-DB may be used as consensus building system.

It is important that the comprehensiveness of Japanese phenomena in the RITE-DB is subsequently considered. There is a possibility that there could be new FEPs added to the RITE-DB and/or that FEPs already in the RITE-DB should be categorized into more detailed FEPs. When new FEPs are added to the RITE-DB, their necessity, in terms of assessment of CO_2 sequestration, has to be considered. It may be fruitful to make a comparison between FEP databases of other countries and the RITE-DB. Making a comparison of uses of FEP database is also important. Also, it may be helpful to discuss the validity of the extracted scenarios with experts.

5. Acknowledgement

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